A Comparative Test in Annealed and Spheroidized Steels after Quenching and Tempering at Different Temperatures

Li, C.S. – B.A. Science, 1924

M.E.
Thesis card

May 30, 1924.

Prof. A. L. Merrill,
Secretary of the Faculty,
Massachusetts Institute of Technology.

Dear Sir :

In compliance with the requirements for the degree of Bachelor of Science, we herewith submit for your approval a thesis entitled '' A Comparative Test in Annealed and Spheroidized Steels after Quenching and Tempering at Different Temperatures ''.

Respectfully,

To

Mr. I. N. Zavarine,

For his valuable suggestions
and assistance, the writers
wish to express their thanks.

Contents

Introduction

During the recent few decades, many researches have been carried out in the subject of heat-treatment. We have now in our possession many processes to bring about the most valuble properties in the simple carbon and alloy stee-ls which our ancesters scarcely heard of. However, we should never rest satisfied with what has been already achieved. Indeed, the subject of heat-treatment is still in its infancy and yet we are as ignorant as ever. For instance, our knowledge with regard to the different aspects of spheroidization is still very meagre.

Though there are few cases in which the effect of spheroidization have been made known, perhaps not a single one has been investigated on the simple carbon and alloys steels with relation to the variation of different tempering temperatures.

The writers, therefore, propose to do ''A comparative test in annealed and spheroidized steels after quenching and tempering at different temperatures.'' With knowledge however imperfect, they hope some contribution might be made or at least common interest might be aroused in the different aspects of spheroidization on steels.

Procedure

(a) Preparations--There are two kinds of steel investigated, namely simple carbon and nickle steels, the compositions of which are given in the data sheet. All together fifty-six specimens are made. For each kind of steel the following operations are carried out.

Before machining, one half of the stock bars cut are annealed in electrical furnaces at a temperature of 1500° F for an hour and the other half spheroidized in a furnace with an automatic recording device for a continuous operation of twenty-four hours. Both of the annealed and the spheroidized stock bars are then cooled with the furnace.

After they are turned into tensile test specimens, the next operation is to quench them in oil at 1525° F. Salt bath is adopted, instead of either electrical or gas furnace in order to prevent oxidation,. for that purpose.

Then four specimens, two of them taken from the annealed and two from the spheroidized group, are tempered for forty-five minutes from tempreatures of 700° F to 1200° F for every 100°degrees. They are are cooled in air. These tempered specimens make a total of twenty-four, with four (two of annealed and two of spheroidized) left untempered as the originals. The grand total is twenty-eight pieces of simple carbon steel and twenty- eight pieces of nickle steel.

(b) Now they are ready to test. The test machine used is the Olsen's autographic test machine. The principle part of this machine different from an ordinary test machine is its recording device controlled automatically by means of electrical contact. While the load is applied to the specimen, a curve plotted with loads in pounds against elongation in inches is gradually built up in a very good shape, from which the load at yield point and the load at maximum point can be readily obtained. Then the area at fractured section and the total elongation are to be measured, after the specimen has been broken. The load at yield point or at its maximum limit divided by the original cross section area will give the stress in pounds per square inch at yield point or its tensile strength of the metal. The difference between the original and the fractured cross sectional area divided by the original cross sectional area will be the per cent in reduction of area. The tatal elongation divided by the gage length, which is two inches for each, will be the per cent of elongation.

Finally Brinell hardness test is made, using 10 milimeter ball and 3000 kilogram pressure. Threading part of the specimen is ground off partly flat giving space sufficient so that several impressions can be made by the Brinell hardness test machine. The diameters are then measured under a microscope. Then the Brinelll numbers are interpreted from a chart, which gives the relation between diameter and hardness number.

Having the test completely made, curves are plotted for each group of specimens with yield point, maximum strength, reduction of area, elongation, and Brinell hardness as ordinates and tempering temperatures as abscissae. In order to indicate the results clearly, curves for both annealed and spheroidized steels are madeo on the same sheet for comparision.

Tention Test

Simple carbon steel, specimen

(A) annealed

(S) spheroidized

Original (without quenching and tempering)

Specimen mark	(A)		(S)	
Gage length, ins.	2	2	2	2
Diameter, in.	.505	.499	.500	.502
Load at Y.P. lbs.	10300	10400	9300	9100
Max. load lbs.	18150	17950	15550	15550
Fract'd diam. in.	.377	.376	.322	.323
Ultimate exten'n in.	2.55	2.50	2.57	2.58
Area of original section sq. in.	.200	.196	.196	.198
Yield point lbs per sq. in.	51700	53100	47300	46000
Maximum load lbs. per sq. in.	90700	91600	79200	78600
Area of fract'd section sq. in.	,112	.111	.081	.082
Reduction of area of cross sect'n %	44.0	43.4	58.6	58.6
Ultimate extension in %	26.9	25.0	28.5	29.0

Tension Test

Simple carbon steel

Specimen (A) annealed at 1500°F

(S) spheroidized

Quenching temperature-1525°F

Tempering temperature-700°F

Specimen mark	(A)		(S)	
Gage length, in.	2	2	2	2
Diameter, in.	.503	.500	.502	.498
Load at Y.P.lbs.	18500	19000	13500	19500
Max. load lbs.	28200	27600	27200	27200
Diameter of fractured sect.in.	.356	.350	.346	.364
Ultimate extension	2.25	2.28	2.34	2.26

Area of orig'l section sq.ins.	.199	.196	.198	.195
Yield point, pounds/sq. in.	98100	97000	93500	100000
Maximum load pds./sq. in.	142000	141000	137000	139600
Area of fractured sect.sq.in.	.0995	.0962	.0940	.104
Reduction of area cross sect. %	50.0	50.9	42.6	46.6
Elongation %	12.5	14.0	17.0	13.0

Tension Test

Simple carbon steel, specimen

(A) annealed

(S) spheroidized

Quenching temperature-1525°F; Tempering temperature-800°F

Specimen mark	(A)		(S)	
Gage length, ins.	2	2	2	2
Diameter, in	.502	.500	.504	.504
Load at Y.P. lbs.	19050	18700	18000	18500
Max. load lbs.	26600	26150	33500	30150
Fract'd diam. in.	.348	.348	.390	.373
Ultimate exten'n in.	2.35	2.33	2.23	2.24

Area of original sect'n sq.ins.	.198	.196	.199	.199
Yield point lbs per sq. in.	96200	95500	90500	93000
Maximum load lbs. per sq. in.	134000	133000	168000	151500
Area of fract'd sect'n sq. ins.	.0951	.0951	.119	.109
Reduction of area of cross sect'n %	52.5	51.5	40.1	45.2
Ultimate exten'n %	17.5	16.5	11.5	12.0

Tension Test

Simple carbon steels specimen

(A) annealed

(S) spheroidized

Quenching temperature-1525 ; Tempering temperature-900°F

Specimen mark	(A)		(S)	
Gage length, ins.	2	2	2	2
Diameter, in.	.499	.501	.504	.503
Load at Y.P. lbs.	19250	20800	18850	18070
Max. load lbs.	26170	27770	26000	20800
Fract'd diam. in.	.353	.374	.340	.360
Ultimate exten'n in.	2.3	2.27	2.38	2.33

Area of original sect. sq. ins.	.196	.197	.199	.199
Yield point lbs. per sq. in.	98300	106000	94500	91000
Maximum load lbs.per sq. in.	133000	141000	130000	130000
Area of fract'd sect'n sq.in.	.098	.110	.091	.102
Reduction of afea of crass sect'n %	50.0	44.2	54.5	48.7
Ultimate exten'n %	15.0	13.5	19.0	16.5

Tension Test

Simple carbon steel, specimen

(A) annealed

(S) spheroidized

Quenching temperature-1525°F;Tempering temperature-1000°F

Specimen mark	(A)		(S)	
Gage length, ins.	2	2	2	2
Diameter, in.	.502	.502	.503	.503
Load at Y.P. lbs.	18000	17000	17000	16100
Max. load lbs.	29400	24000	23750	23520
Fract'd diam. in.	.345	.333	.328	.342
Ultimate exten'n in	2.35	2.37	2.39	2.40

Area of original sect. sq. in.	.198	.198	.199	.199
Yield point lbs. per sq. in.	90900	85900	85500	83500
Maximum load lbs. per sq. in.	126000	121000	119500	118000
Reduction of area of gross sect'n %	52.5	56.0	57.5	53.8
Ultimate exten'n %	17.5	18.5	19.5	20.0
Area of fract'd section sq. in.	.094	.087	.084	.092

Tension Test

Simple carbon steel, specimen

(A) annealed

(S) spheroidized

Quenching temperature-1535°F;tempering temperature-1100°F

Specimen mark	(A)		(S)	
gage length, ins.	2	2	2	2
Diameter, in.	.498	.498	.503	.503
Load at Y.P. lbs.	16300	16300	16050	10650
Max. load lbs.	22750	22500	21820	21270
Fract'd diam. in.	.323	.317	.325	.321
Ultimate exten'n in.	2.35	2.44	2.44	2.49

Area of original sect'n sq. in.	.195	.195	.199	.199
Yield point lbs. per sq. in	83600	83600	80700	78700
Maximum load lbs per sq. in	117000	115000	109600	107000
Reduction of area of cross sect'n %	57.9	59.5	58.3	59.3
Area of fract'd section sq. in.	.082	.0789	.083	.081
Ultimate exten'n %	17.5	22.0	22.0	24.5

Tension Test

Simple carbon steel, specimen

(A) annealed

(S) spheroidized

Quenching temprrature-1525;tempering temperature-1200°F

Specimen makk	(A)		(S)	
Gage length, ins.	2	2	2	2
Diametrr, inch	.497	.499	.503	.503
Load at Y.P. lbs.	16900	15500	14750	15100
Max. load lbs.	20600	20750	18800	18620
Fract'd diam. in.	.307	.307	.319	.323
Ultimate exten'n in	2.52	2.48	2.56	2.56

Area of original section in.	.194	.196	.199	.199
Yield point lbs. per sq. in.	87100	79100	74200	76100
Maximum load lbs. per sq. in.	106000	106000	99600	98900
Area of fracted section sq. in.	.0740	.0740	.0799	.0819
Reduction of area of cross sect'n %	61.8	62.2	59.8	58.8
Ultimate exten'n %	26.0	24.0	28.0	28.0

Tension Test

Nickle steel, specimen

(N) annealed

(P) spheroidized

Original (without quenching and tempering)

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.502	.502	.496	.504
Load at Y.P. lbs.	12500	11850	9500	9500
Max. load lbs	19000	19100	21750	22300
Fractured diam. in	.331	.334	.375	.360
Ultimate exten'n in.	2.56	2.56	2.45	2.44

Area of original section sq. in.	.198	.198	.193	.200
Yield point lbs. per sq. in.	63100	60000	49200	47500
Maximum load lbs, per sq. in.	96000	96500	112700	111500
Area of fractured section sq. in.	.0860	.0876	.1100	.1020
Reduction of area of cross sect'n %	66.7	65.8	43.0	49.0
Ultimate extension in %	28.0	28.0	22.5	22.0

Tension Test

Nickle steel, specimen

(N) annealed

(P) spheroidized

Quenched at 1525°F and tempered at 700°F

Specimen mark	(N)		(P)	
Gage length, inch	2	2	2	2
Diameter , inch	.500	.503	.503	.505
Load at Y. P. lbs.	33900	34000	34000	34000
Max. load lbs.	36900	37200	38400	38550
Fract'd diam. in.	.330	.330	.346	.353
Ultimate exten'd in.	2.25	2.28	2.25	2.25

Area of original section sq. in.	.196	.199	.199	.200
Yield point lbs. per sq. in.	173000	171000	171000	170000
Maximum load lbs. per sq. in.	188000	187000	193000	193000
Area of fractured section sq. in.	.0855	.0855	.0940	.0979
Reduction of area of cross section%	56.4	57.0	52.7	51.1
Ultimate exten'n in %	12.5	14.0	12.5	12.5

Tension Test

Nickle steel, specimen

(N) annealed

(P) spheroidized

Quenched at 1525°F and tempered at 800°F

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.499	.501	.504	.503
Load at Y.P. lbs.	30600	31000	31000	31000
Max. load lbs.	33000	33250	34350	34050
Fractured diam. in.	.322	.322	.331	.324
Ultimate exten'n in.	2.29	2.29	2.27	2.26

Area of original section sq. in.	.195	.197	.199	.199
Yield point lbs. per sq. in.	157000	157000	155300	156000
Maximum load lbs. per sq. in.	169000	169000	172100	171200
Area of fract'd section sq. in.	.0814	.0814	.0860	.0824
Reduction of area of cross section %	58.3	58.7	56.9	58.5
Ultimate extension im %	14.5	14.5	13.5	13.0

Tension Test

Nickle steel, specimen

(N) annealed

(P) spheroidized

Quenched at 1525°F and tempered at 900°F

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.503	.503	.502	.502
Load at Y.P. lbs.	278000	27800	27200	28500
Max. load lbs.	29950	29900	29900	28500
Fractured diam. in,	.319	.320	.324	.324
Ultimate exten'n in.	2.32	2.34	2.32	2.31

Area of original section sq. in.	.199	.199	.198	.198
Yield point lbs. per sq. in.	140000	140000	137200	144000
Area of fractured section sq. in.	.0799	.0804	.0824	.0824
Reducton of area of cross section %	59.7	59.6	58.4	58.4
Ultimate extension in %	16.0	17.0	16.0	15.5

Tension Test

Nickle steel, specimen

(N) annealed

(P) spheroidized

Quenched at 1525°F and Tempered at 1000°F

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.504	.502	.503	.504
Load at Y.P. lbs.	24800	24650	24600	24600
Max. load lbs.	27050	26750	27300	26900
Fractured diam. in.	.313	.312	.317	.315
Ultimate exten'd in	2.40	2,38	2,36	2.36

Area of original section sq. in.	.199	.198	.199	.199
Yield point lbs. per sq. in.	124000	124500	124000	123400
Maximum load lbs. per sq. in.	135500	135200	137000	135000
Area of fractured section sq. in.	.0769	.0765	.0789	.0779
Reduction of area of cross section %	61.5	61.4	60.2	60.9
Ultimate extension in %	20.0	19.0	18.0	18.0

Tension Test

Nickle steel, specimen
(N) annealed
(P) spheoidized

Quenched at 1525°F and tempered at 1100°F

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.502	.502	.505	.502
Load at Y.P. lbs.	21100	21150	2075	20600
Max. load lbs.	23750	23950	23750	23450
Fractured diam. in.	.296	.297	.296	.296
Ultimate exten'n in	2.45	2.45	2.44	2.46

Area of original section sq.in.	.198	.198	.200	.)98
Yield point lbs. per sq. in.	106500	107000	103750	104000
Maximum load lbs. per sq. in.	120000	121000	118750	118500
Area of fractured section sq. in.	.0688	.0693	.0688	.0688
Reduction of area osf cross section %	65.2	65.2	65.6	65.2
Ultimate extension in %	22.5	22.5	22.0	23.0

Tension Test

Nickle steel, specimen
(N) annealed
(P) spheroidized

Quenched at 1525°F and tempered at 1200°F

Specimen mark	(N)		(P)	
Gage length, inches	2	2	2	2
Diameter, inch	.502	.502	.501	.501
Load at Y. P. lbs.	16850	16300	16800	16750
Max. load lbs.	22150	22100	21950	21900
Fractured diam. in.	.295	.305	.295	.294
Ultimate exten'n in.	2.53	2.53	2.54	2.55

Area of original section sq. in.	.198	.198	.197	.197
Yield point lbs. per sq. in.	85200	82400	85250	85100
Maximum load lbs. per sq. in.	111800	111600	111400	111100
Area of fractured section sq. in.	.0683	.0731	.0683	.0679
Reduction of area cross section %	65.6	63.2	65.3	65.5
Ultimate extension in %	26.5	2y.5	27.0	27.5

Tabulation of Data and Results

I. Simple Carbon Steel

Steel composition (S.A.E. No. 1045)

C...... .45-.50 Mn..... .35-.60 P..... .045 (max.)

S...... .05 (max.) Si..... .32

Diameter of specimen, 0.5 inch

Gage length, 2.0 inches

Brinell test; 10 mm. ball, 3000 kg. pressure

Tempering temperature	Yield point lbs/sq.in.	Max. load lbs/sq.in	Reduction of area %	Elongat'n %	Brinell hardness
(a) Annealed at 1500°F and then quenched in oil at 1525°F					
Original	52,400	91,100	43.6	45.9	178
700° F	97,600	142,000	50.9	13.7	270
800	95,900	134,000	52.0	17.0	254
900	102,000	187,000	47.2	14.7	265
1000	88,400	123,000	54.2	18.0	251
1100	83,600	116,000	58.7	19.7	217
1200	83,100	106,000	62.0	25.0	211
(b) Spheroidized and then quenched in oil at 1525°F					
Original	47,200	78,900	58.6	28.5	155
700° F	96,700	138,000	44.6	15.0	265
800	92,000	160,000	42.6	12.0	286
900	92,700	130,000	51.6	17.6	272
1000	84,600	119,000	55.6	19.7	222
1100	84,700	108,000	58.8	22.2	223
1200	75,100	99,200	59.3	28.0	191

II Nickle Steel

Steel composition (S.A.E. No. 2335)

C...... .30-.40 Mn..... .50-.80 S.... .045(max.)

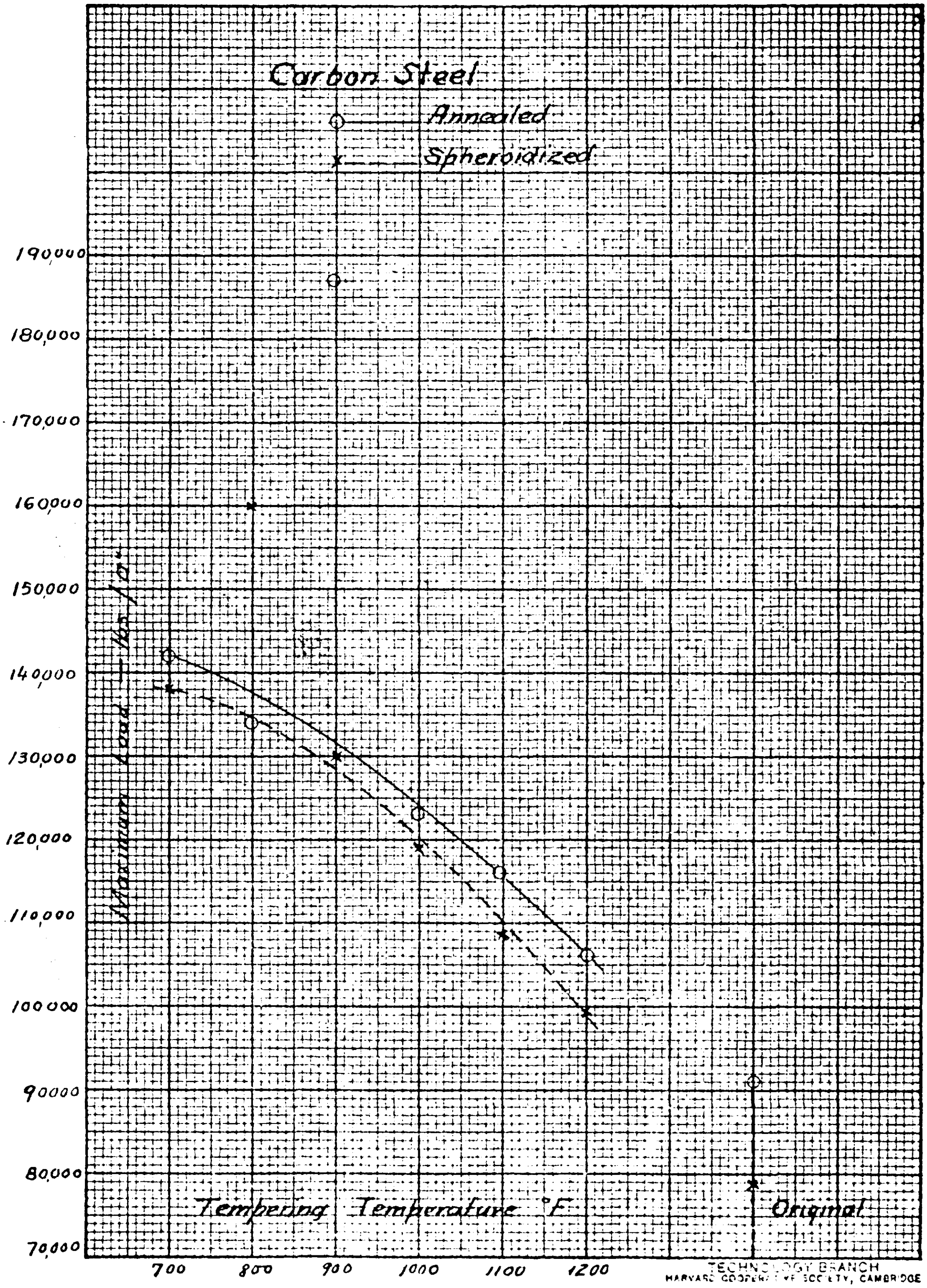
Ni..... 3.25-3.75

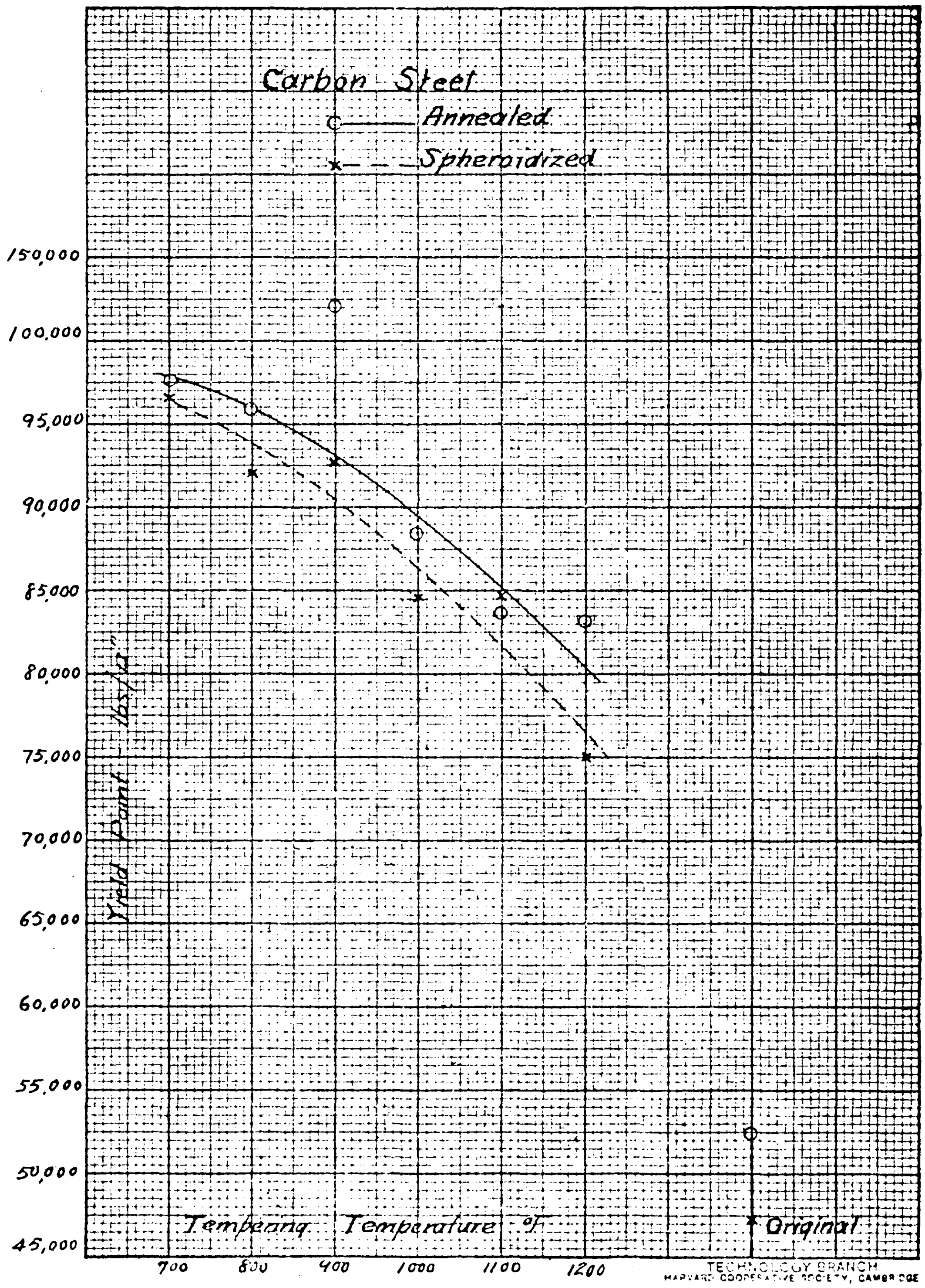
Diameter of specimen, 0.5 inch

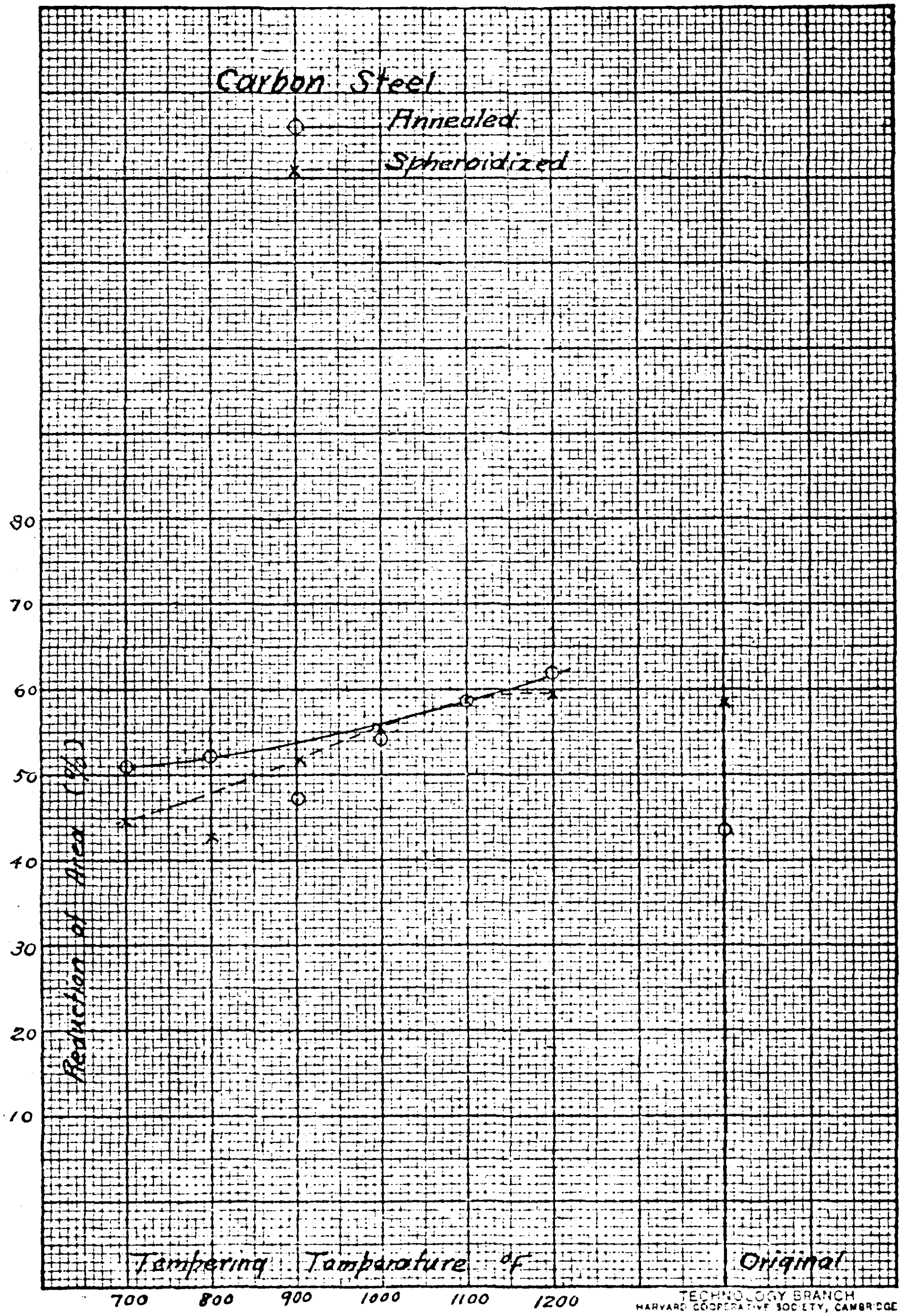
Gage length, 2.0 inches

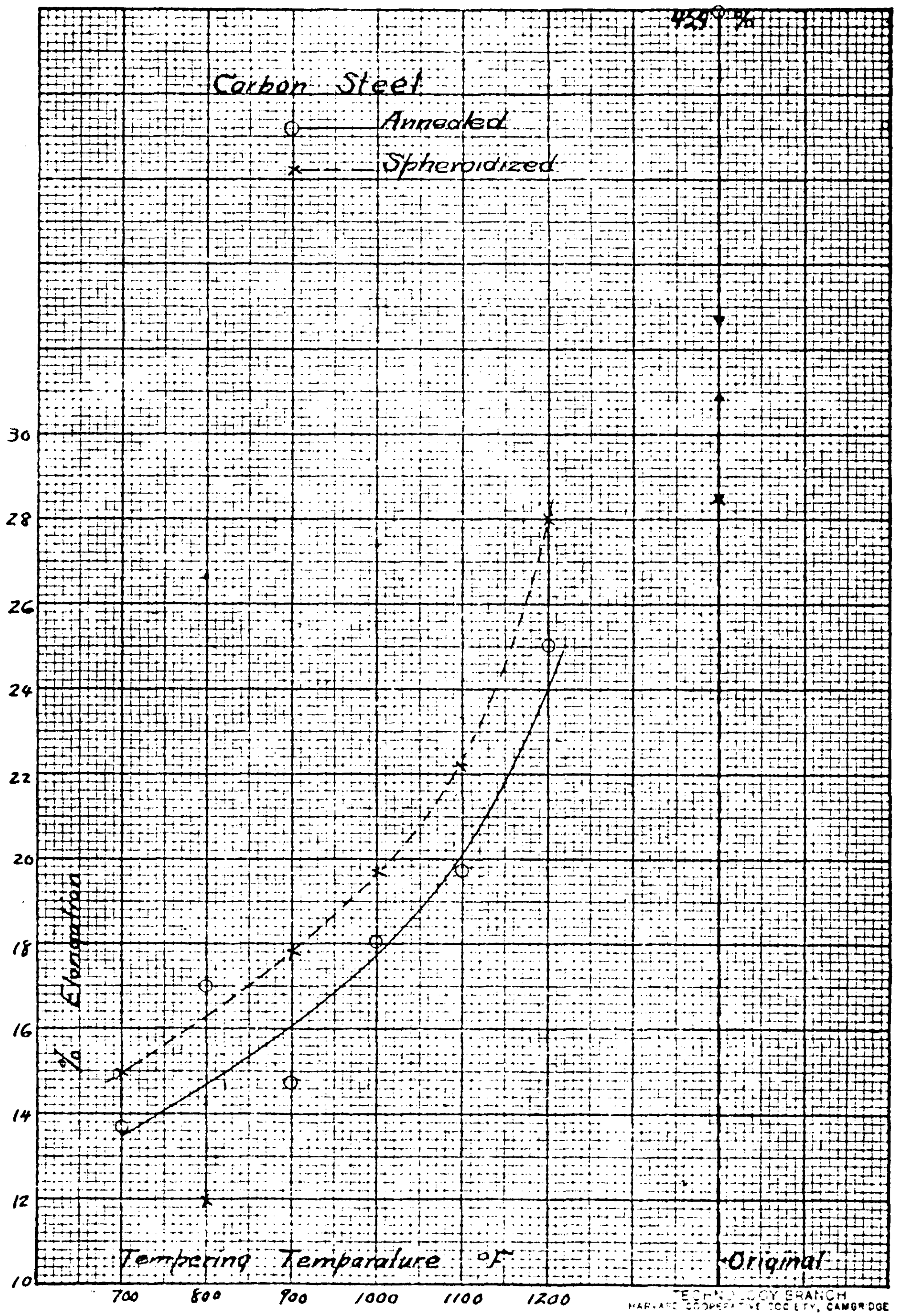
Brinell test; 10 mm. ball, 3000 kg. pressure.

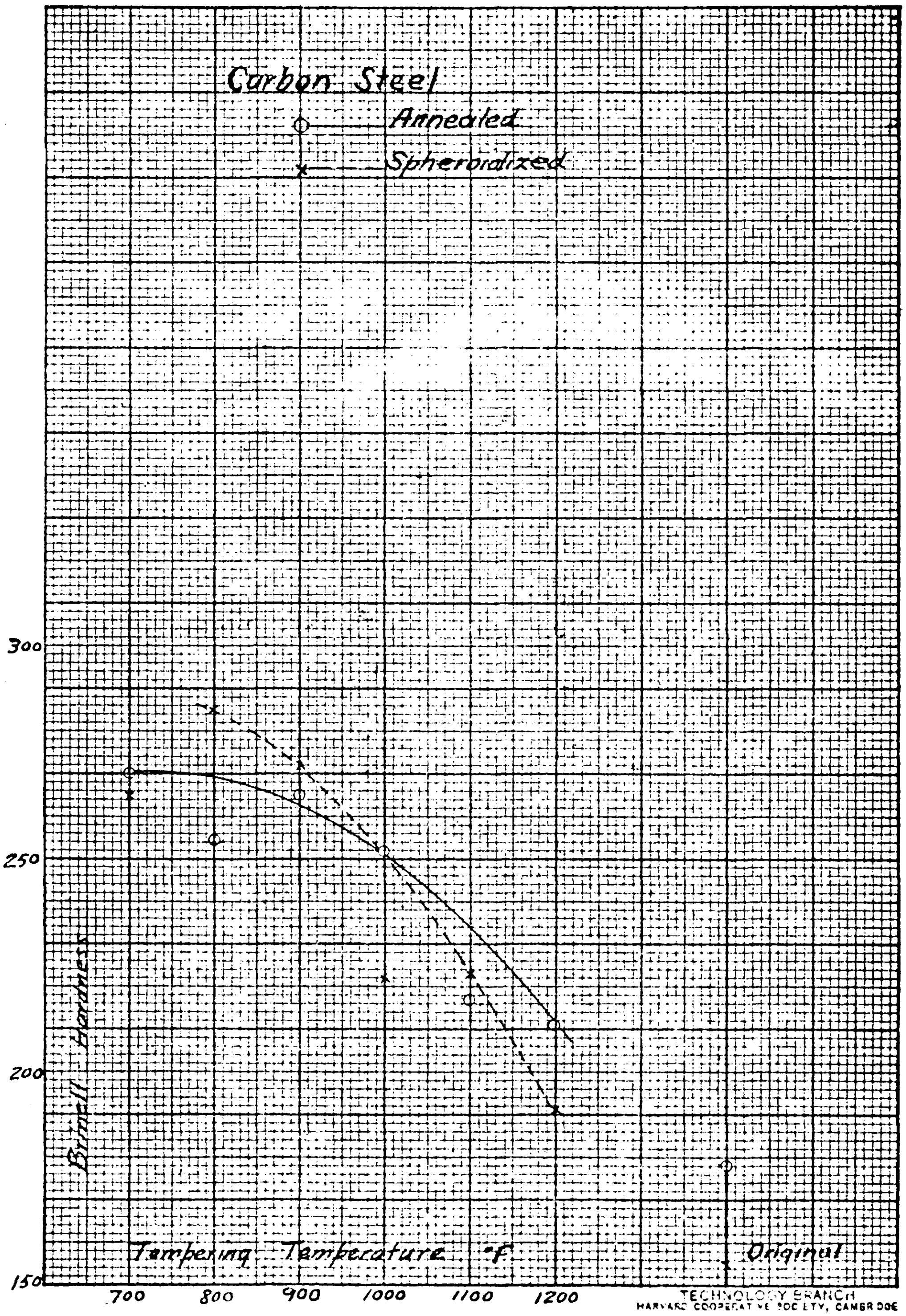
Tempering temperature	Yield point lbs/sq.in.	Max. load lbs/sq.in	Reduction of area %	Elongat'n %	Brinell hardness
(a) Annealed at 1500°F and then quenched in oil at 1525°F					
Original	61,550	96,250	66.3	28.0	183
700° F	172,000	187,500	56.7	13.3	388
800	157,000	169,000	58.5	14.5	369
900	140,000	150,500	59.6	16.5	341
1000	124,300	135,300	61.4	19.5	298
1100	106,700	120,500	65.2	22.5	255
1200	83,800	111,700	64.4	26.5	232
(b) Spheroidized and then quenched in oil at 1525°F					
Original	48,350	112,100	46.0	22.2	223
700	170,500	193,000	51.9	12.5	415
800	155,700	171,100	57.7	13.2	369
900	140,600	154,400	58.4	15.7	331
1000	123,700	136,000	60.5	18.0	289
1100	103,900	118,600	65.4	22.5	255
1200	85,180	111,250	65.4	27.2	215

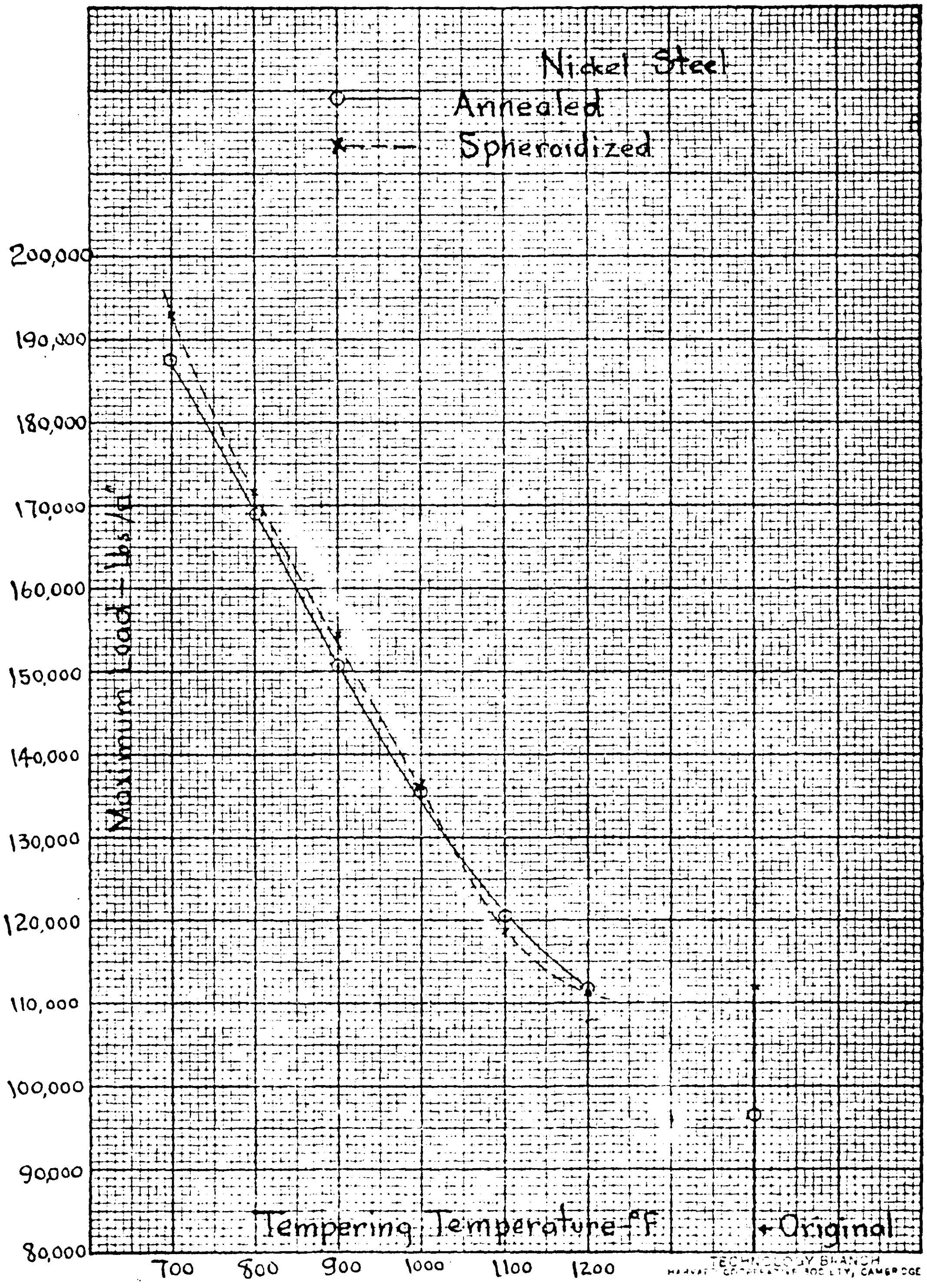

Carbon Steel
○——— Annealed
x- - - - Spheroidized
190,000
180,000
170,000
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90000
80,000
70,000
Maximum Load — lbs./□"
Tempering Temperature °F
Original
700
800
900
1000
1100
1200

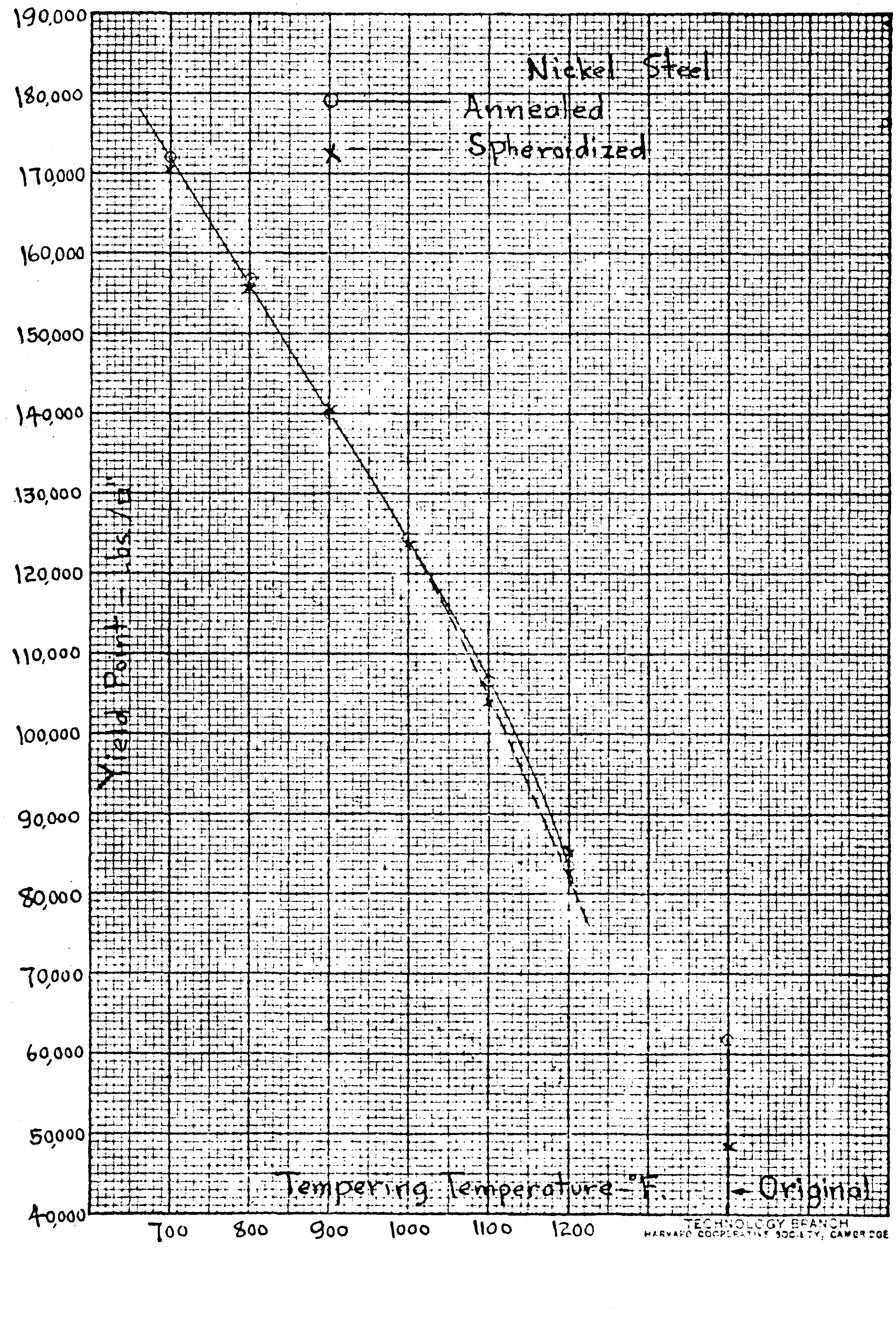

Carbon Steel
Annealed
Spheroidized
150,000
100,000
95,000
90,000
85,000
80,000
75,000
70,000
65,000
60,000
55,000
50,000
45,000
Yield Point lbs/□"
Tempering Temperature °F
Original
700
800
900
1000
1100
1200
TECHNOLOGY BRANCH
HARVARD COOPERATIVE SOCIETY, CAMBRIDGE

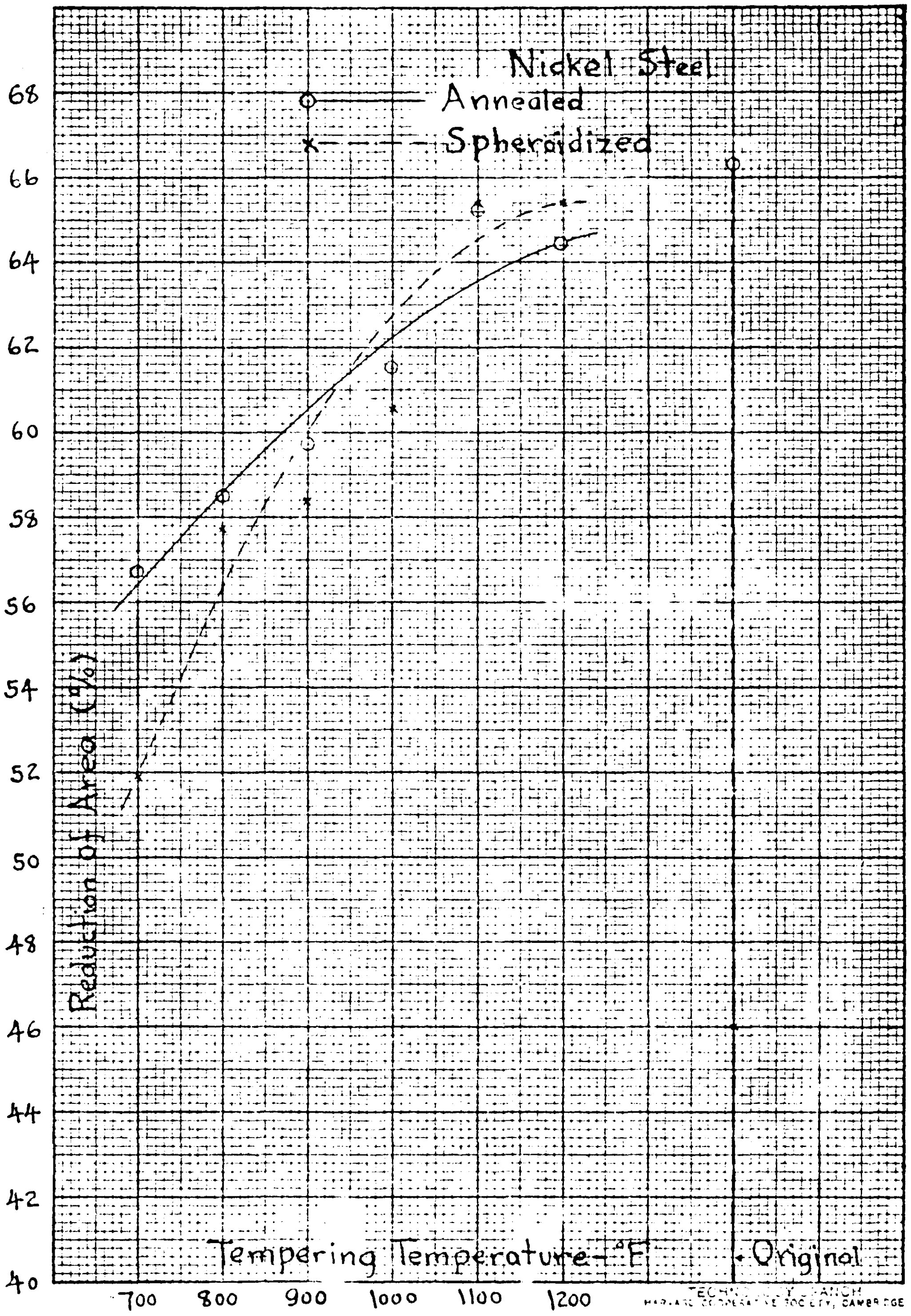

Carbon Steel
Annealed
Spheroidized
80
70
60
50
40
30
20
10
Reduction of Area (%)
Tempering Temperature °F
Original
700
800
900
1000
1100
1200

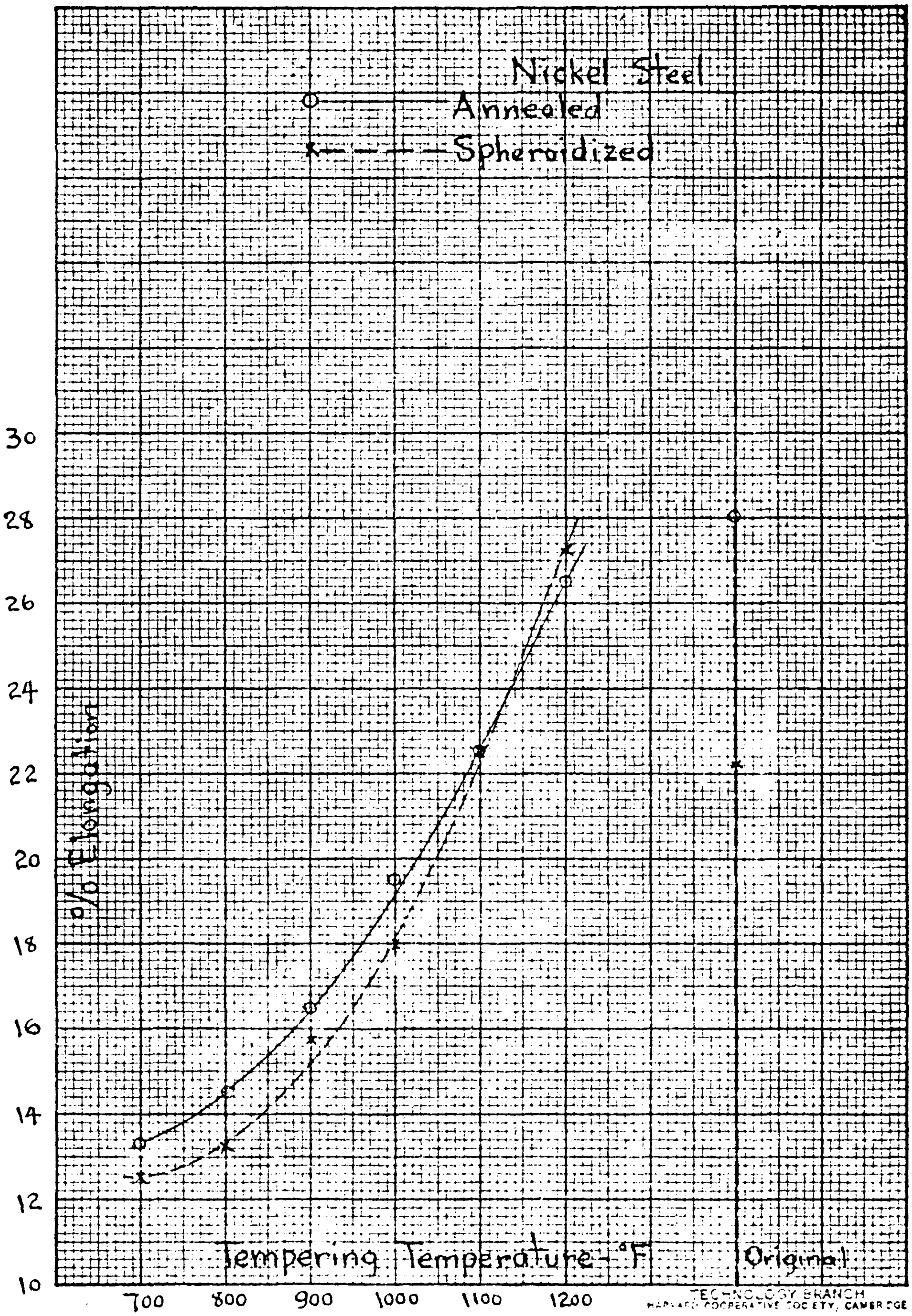

42.5 %
Carbon Steel
Annealed
Spheroidized
% Elongation
30
28
26
24
22
20
18
16
14
12
10
Tempering Temparature °F
Original
700
800
900
1000
1100
1200

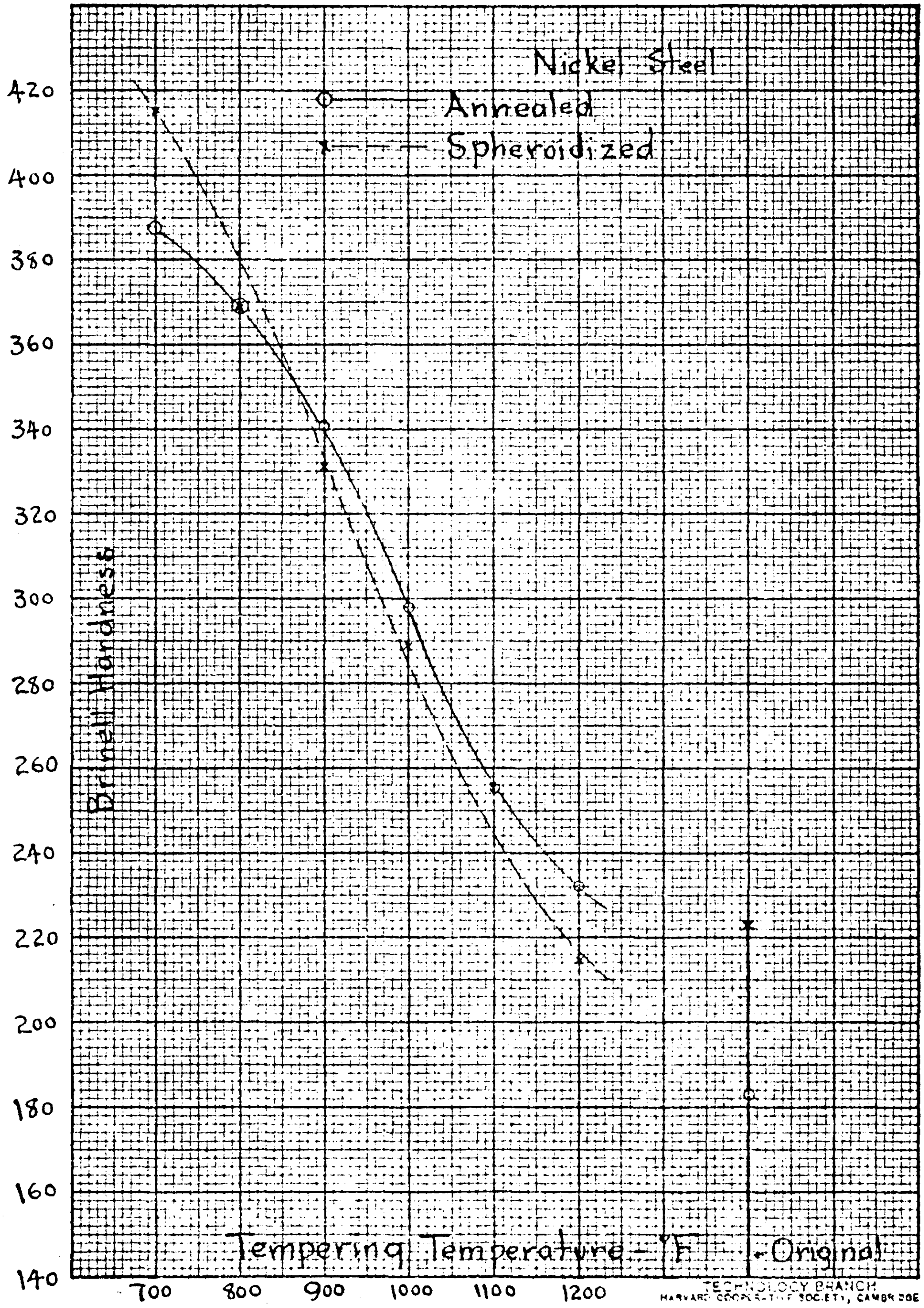

Carbon Steel
Annealed
Spheroidized
Brinell Hardness
300
250
200
150
Tempering Temperature °F
Original
700
800
900
1000
1100
1200


Nickel Steel
Annealed
Spheroidized
200,000
190,000
180,000
170,000
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90,000
80,000
Maximum Load - Lbs/□"
Tempering Temperature °F
+ Original
700
800
900
1000
1100
1200


Nickel Steel
Annealed
Spheroidized
Yield Point — lbs/□"
190,000
180,000
170,000
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
Tempering Temperature °F.
← Original
700
800
900
1000
1100
1200


Nickel Steel
Annealed
Spheroidized
Reduction of Area (%)
68
66
64
62
60
58
56
54
52
50
48
46
44
42
40
Tempering Temperature – °F
Original
700
800
900
1000
1100
1200


Nickel Steel
Annealed
Spheroidized
30
28
26
24
22
20
18
16
14
12
10
% Elongation
Tempering Temperature - °F
Original
700
800
900
1000
1100
1200


Nickel Steel
Annealed
Spheroidized
Brinell Hardness
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
Tempering Temperature – °F
700
800
900
1000
1100
1200
←Original

General Discussions
On Spheroidization

As a brief statement of the causes and formation of the globular cementite might be helpful to a proper appreciation of the final results, a few pages will be devoted to the subject of spheroidization in general.

In ordinary steels, the cementite and ferriite exist in lamellar form. After proper heat-treatment, the lamellar cementite elements will disappear to form into globular cementite elements. This is simply a manifestation of the complex materials toward structural equilibrium: Elements of structure of similar kinds tend to unite and form coarser elements and the contours of these elements tend to become rounded on account of surface tension.

In mixtures of two phases, such as cementite and ferrite, spheroidization or coalescence may be brought about under two sets of conditions, namely; (1) at constant temperatures and (2) at falling temperatures.

(1) At constant temperatures--Here spheroidization depends upon the solubility of the structural elements, which in turn is determined by their state of deformation, the radii of their curves, and their diffusion in the solid state. Hence the original dimensions of the particles and their state of internal stress are

impoertant. As rate of diffusion is faster at high temperature, high temperature favors spheroidization.

(2) At falling temperatures--Here in adddition to the factors mentioned above are added influence of crystalline germ-forms, heterogeneity of solid solutions the variation of solubility with the temperature, the faculty of spontaneous crystallization an-d the linear rate of crystallization.

These various factors lead to the formation of rounded cementite, called globular or spheroidal cementite. In steels of low carbon content, the coalescence of the cementite reveals itself by the pearlite area becoming bounded by a belt of partly formed cementite with ragged edges. Before the lamellar cementite has been completely transformed to the globular cementite, it reaches an intermediate stage when one can detect strands of spherules.

In case of hyper-eutectic carbon steels, distinction should be made between the coalescence of the pro-eutectic cementite below Acm and above A_1 and that of the eutectic cementite below A_1. In the former case, the solubility of the cementite depends upon greatly the temperature while in the later case , it is independent of the temperature. As the different factors influence the properties of steel differently according as the temperature zone is above or below A_1, we have to discuss the different factors accrodig to the following classifications.

I For steels of the same composition

(a) Above A_1

(1) Rate of cooling

(2) Temperature and duration of initial heating.

(3) Temperature alternations aboveA A_1

(b) Below A_1

(4) Temperature and duration of maintenance at this temperature.

(5) Previoys mechanical working.

(6) Original fineness of the cementite elements (troostite or sorbite).

II For steels of different compositions (the preceeding six factors remaining constant)

(7) Carbon content

(8) Presence of elements other than carbon.

Let us take a brief survey of the effect of these various factors on spheroidization.

I. Above A_1

(1) Rate of cooling-- Below Acm and above A_1, and during the passage through A_1, cooling

favors coalescence. It is because more time given for the process to take place. Below A_1, the effect of cooling is practically negligible, though it still favors coalescence.

(2) Temperature and duration of heating above A_1-- Above Acm, heating of hyper-eutectic steel leads to the solution of free cementite and the higher the temperature the greater the solubility. Hence heating above Acm and duration of heating tend to hiner the formation of globular cementite.

(3) Alternation of temperature during the passage of A_1-- This is one of the most effective ways to produce coalescence. During the period of heating, the small particles of cementite on account of their minute dimensions and great solubility dissolve first, while during the period of cooling, they precipitate around the residual particles of cementite. The cementite particles consequently become coarser. In fact, every alternation of temperature about A_1 decreases the number and increases the size of cementite particles.

II. Below A_1

(4) Temperature and duration of heating below A_1--Coalescence can be made to occur at tempera-

ture below A_1 by greatly prolonged heating, lasting for 1000 hours or so. The nearer to A1, the heating is carried out, the more comparative quickly coalescence will occur. Also materials which have been cold-worked will be spheroidized quickly than those which have not.

(5) and (6) Previous mechanical work and original fineness of the cementite elements (troostite or sorbite state)--The cementite lamellae must be previously broken up before they can assure globular form. Hence, mechanical work such as forging and cold work will help spheroidization of cementite by previously breaking their plates of lamellar cementite. Permanent or elastic deformation produced by cold wrok increases the solubility of the cementite in ferrite and thereby favours spheroidization. The fineness of the cementite elements will also favour spheroidization due to variation in solubility. coalescence will take place more rapidly, if sorbite or troostite be present. On account of this double influence of plastic deformation and fineness of structure, forged steel can be spheroidized much more easily.

The part played by heating below

A_1 may be summed up as follows :-

(1) With steels which have been previously cold-worked, heating below A_1 will make coalescence to take place and the quicker it will occur, the higher the heating temperature.

(2) With annealed steels, heating below A_1 will produce coalescence unless the duration is extremely long.

(3) The rate of cooling below A_1 has no effect on coalescence.

(4) Chemical composition--Not much has been known on this subject yet. We shall put down a few instances only. In steels of eutectic composition it is much difficult for coalescence to take place. In hyper-eutectic steels, the readieness to form coalescence increases with the percentage of carbon. Low percentages of chromium and tungsten make the coalescence of steels containing 1.0 to 1.2 per cent of carbon more difficult, while higher per centages of chromium, tungsten, and molybdenum cause complete coalescence of the carbon.

Spheroidization and the properties and heat-treatment of steels.

(1) Influence on hardness--For most steels

softness obtained from annealing is sufficient for ease in machining. But for certain steels, which are particularly hard owing to their chemical composition, ordinary annealing is not sufficient and we have to resort to divorcing annealing or spheroidization. In such cases, the resultant softness is a function of the degree of spheroidization aquired by the cementite elements. The more the spheroidization is, the softer the material will be.

(2) Influence on the malleability, in the cold.--Spheroidization steels are very valuble in such operations as stamping-dies, and drawing tabes, owing to their possessing lower elastc limit and greater percentage of elongation. Such processes as alternations of cold-working and annealing are really nothing more than spheroidizing the cementite elements in the metal. Investigations into materials giving unsatisfactory results in die stamping often show that such materials posess lamellar structure.

(3) Influence on the surface finishing after machining--Though globular structure is generally desirable in machining for its softness and ease of manipulation, it is not good for machine parts where accurate surface finishing is required. For such works, the globular structure if existing in the material should be destroyed by proper annealing.

(4) Influence on the chemical properties --Spheroidizafion changes not only the physical properties of steel but modifies its susceptibility to chemical agents as well. For instance, spheroidizied steel is less soluble in sulphuric acid than annealed steel of lamellar structure. Not much has yet been known on this subject.

(5) Influence on the heat-treatments-- Dissolution of the carbon on heating is more difficult to obtain in spheroidized steels. It is due to the fact that in such steel the intersolubility of the structure elements as a whole t-ends towards a minimum, their area of contact is reduced and radius of curvature is changed. Thus in order to get the same mechanical results with the same hardening process, the period of heating should be much prolonged and the number of quenchings increased in the case of spheroidized steels. The important point to note here is that heat treatment proves to be a function of its initial structure and therefore its previous treatment as well as of its chemical composition. From this arise two alternative solutions of the problem of heat-treatment of a steel of given chemical composition; the second one being to be preferred :-

(a) To adopt the final heat-treatment to the existing structural state of the steel.

(b) To change the initial structural state of the steel to a standard structural condition (which shall always be constant) by a preliminary heat-treatment and then adopt a uniform final heat-treatment.

Effect of Nickle on Carbon Steels

The first set of our specimen is of carbon steel while the second is of nickle steel. A short statement of the effect of nickle on the physical properties of carbon steel will be given, as the writer-s think that it might help to explain the difference in results between the two sets of tests made. Their nickle steel specimens being of 3.25 to 3.75 % nickle, they will confine their discussion more or less to nickle steel of about the same amount in composition Such Steels are called pearlitic nickle steels on account of their forming pearlites when air cooled. They are the most widely used of all nickle steels. Compared with carbon steels of equal ductility, they show a much a higher tensile strength and especially higher elastic limit;while compared with carbon steels of equal elastic limit, they show much greater ductility. In other words, with such nickle steels, it becomes possible to secure high tensile strength or elastic limit with little decrease in ductility. Nickle steels stand better to wear owing to their slight increase in hardness and, with proper heat-treatment, will also show greater resistance to shock.

Nickle steels of various percentages of nickle in them serve many purposes where carbon steels have shown themselves to be inadequate. As early as 1904, researches were made on nickle steels to determine whether or not it could be used as boiler tubes with some advantage. Tests have shown considerable advantages under boiler conditions as regards to corrosion and alterating expansion and contraction. Another interesting use to which nickle steels have been put is for springs. Many tests on nickle steels containing various proportions of nickle have been made to discover the one which shows the best variation in modulous of elasticity with variation of temperature. With regard to friction, nickle steel offers 6 to 10 % less than carbon steel. The use of nickle steel in bridges and structural designs is known to all.

Discussions on Results

(A) Simple carbon steel

(1) Maximum load curve--The plot for the original specimen shows that spheroidization decreases the tensile strength.~~af~~ After quenching and tempering, spheroidization has the same effect on the tensile strength. The plot shows that with the increase of the tempering temperature , the tensile strength of both the annealed and spheroidized steels decreases. At all tempering temperatures annealed steel specimens give us higher tensile strength htan the spheroidized. At about 900° F the spheroidized steel approaches the annealed most closely as shown in the curve. At 700° F the difference betwen the tensile strength of the annealed and the spheroidized is about 4,000 pounds per square inch and decreases as the tempering temperature increases towards 900°F. From 900°F on the curve diverges again with a maximum difference of about 6,500 pounds per square inch at 1,200°F.

(2) Yield point plot--This plot is similar in nature to the previous one. Quenching and tempering raise the yield point of both the annealed and the spheroidized steels a great deal as we should expect. The annealed steels show higher yield point than spheroidized, throughout the whole tempering

range.

(3) Elongation plot--Percentage of elongation and reduction of area are not always correct indications of ductility. The fracture ought to occur at the middle. But owing to the fact that the middle section is not always the smallest, the fracture does sometimes occur near the fillet of the specimen. In that case the reduction of area and the percentage of elongation will of course be different from what they should ~~they~~ be. The mistake introduced in percentage of elongation is fortunately not very big, because the variation is usually only a small percentage of the gage length; that introduced in reduction of area is however, more serious since the cross sectional area is small. Therefore, for ductility elongation is more reliable than reduction of area.

The original specimens show that spheroidization is undesirable for steels not heat treated. After tempering, however, the spheroidized specimens show better results than the annealed, the ductility of the latter having dropped way down. With the increase of the tempering temperature, the ductility of both the spheroidized and annealed steels increases. Further more the slope of the curve also increases, showing that the percentage of elongation is increasing more and more rapidly. After 1,100°F and especially after 1,200°F the rate of increase in elongation is very rapidly. An increase of 50° in tempering temperature would increase the elongation of both the annealed and spheroidized specimens about 4%, the rate of increase being practically the same for both at all tempering temperatures from 700 to 1200°F.

(4) Reduction of area plot--This plot is not very smooth. This is chiefly due to the reasons mentioned above. Its nature should be simalar to the percentage of elongation plot. The spheroidized original specimen shows greater reduction of area than the annealed, as we expect. After heat-treatment , howevr, the annealed steel becomes more ductile than the spheroidized. It is interesting to note that at a tempering temperature of about 1100°F the spheroidized steel becomes just as ductile as it is before quenching and tempering.

(5) Brinell Hardness-plot--The results obtained from the Brinell test is not very satisfactory due to the inhomogeneity of the material. This plot ought to have a nature similar to that of the maximum load plot. Hence the spheroidized and annealed plots should not cross each other. Those two points at

800° and 900°F are not reliable: The former specimens give us inconsistant results throughout our test, while the latter gives us a value a little too high owing to, most probably, inhomogeneity of the material. With the increase of the tempering temperature, the hardness of both the spheroidized and annealed steels decreases.

* * *

(B) Nickle Steel

(1) Maximum load plot--Here the annealed and spheroidized steel cross each~~n~~ other at 1040°F, the phenomenon which has not been observed in the simple carbon steel. Within our tempering range the difference in maximum load between the annealed and spheroidized steels is very small, the greatest being only 5000 pounds per square inch at 700°F. At tempering temperatures below 1040°F the spheroidized steel has greater maximum load than the annealed, while those above it are in favour of the annealed. The average difference is not big in both cases, being only about 2000 pounds persquare inch. By comparing the values for the original specimens with those heat-treated ones we see that heat-treatment raises the tensile strength of both the annealed and the spheroidized steels considerably, especally at lower tempering temperatures.

The gain from heat-treatment is greater in case of annealed steels than that of the spheroidized.

(2) Yield point plot--In original specimens the yield point of the spheroidized steel is lower than that of the annealed which should not be the case. The mistake was introduced in determining the yield point of the former by estimating from the load-elonation curve recorded by the Olsen's test machine. Up to 1000°F the yield point of the annealed specimens and that of the spheroidized are the same. After 1000°F the two plots diverge a little with the annealed above the spheroidized. But the difference is very small, being only about 1000 pounds persquare inch. Hence so far as the yield point is concerned, spheroidized steels are not so good as the annealed.

(3) Elongation plot--The original specimens show us that spheroidization reduces the percentage of elongation of the steel. After heat-treatment this is still true so long as the tempering temperature is below 1150°F. But with higher tempering temperatures the spheroidized specimens show greater elongation thanthe annealed. The average difference in percentage elongation between the annealed and spheroidized steels is about 12 % betweenn tempering temperatures of 700 and 1000°F,

While that at 1200°F is only about .7 %.

(4) Reduction of area plot--This plot is not very reliable, for resons stated above. The spheroidized and annealed plots seem to cross each other at 950°F with the annealed above the spheroidized at lower tempering temperatures and the spheroidized above the annealed at higher temperatures.

(5) Brinell hardness plot--In the original state the spheroidized steel is harder than the annealed, which is contrary to the case in simple carbon steel. The anneealed and spheroidized plots cross each other at 860°F with the spheroidized above the annealed at lower tempering temperatueres and the annealed above the spheroidized at higher temperatures.

Summery--The simple carbon steel plots are not so smooth as the nickle steel ones. This may be due to either that nickle makes the material more homogenious or that it makes the heat-treatment more uniform. In the case of simple carbon steel by means of spheroidization we gain about 9 % in percentage of elongation and loss an average of about 3 % in tensile strength. On the other hand, spheroidization in nickle steel at low tempering temperatures gives us a maximum increase of about 2.6 % in tensile strength and a dcrease of about 7.7 % in elongation. At high tempering temperatures, however, the contrary is true. The gain in tensile strength at any tempering temperature within our range is not great in nickle steels. Incidently the plots also show that the original steels are much improved by proper heat-treatment in case of both annealed and spheroidized steels.

Conclusion

All the physical properties considered, it probably does not pay to go through the trouble of spheroidization in either carbon or nickle steels, especial~~l~~ly in the latter. Spheroidization, however, has its advantages, when certain properties of steel are required. When tensile strength is the most important, the writers should recommend the use of spheroidized nickle steels tempered at low temperatures. This statement is, however, made without considering the relative prices of nickle and simple carbon steels or the relative expenses of annealing and spheroidization. When ductility is most important, spheroidized simple carbon steels ~~should~~ are to be preferred. 1200°F seems to be a good tempering temperature for that purpose. When both tensile strength and ductility are important, the little gain in tensile strength does not compensate the loss in ductility by spheroidization at lower tempering temperatures; nor will the little gain in ductility by spheroidization at high tempering temperature offset the loss in tensile stregth in case of nickle steels. On the contrary, in case of simple carbon steels, it may be desirable to spheroidize them, if spheroidization does not require any extra expense. When softness for ease of machining is urgently needed, spheroidization will be helpful, if it is followed by tempering at high temperatures.

The End